Renewable and Sustainable Energy Reviews 14 (2010) 2426–2433

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Market penetration of biodiesel

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ARTICLE INFO

Article history:
Received 25 March 2010
Accepted 26 May 2010

Keywords:
Agricultural sector model
Alternative energy
Biodiesel
Emission trading
Carbon equivalent price

ABSTRACT

This research examines in detail the technology and economics of substituting biodiesel for diesel #2. This endeavor examines three areas. First, the benefits of biodiesel are examined, and the technical problems of large-scale implementation. Second, the biodiesel production possibilities are examined for soybean oil, corn oil, tallow, and yellow grease, which are the largest sources of feedstocks for the United States. Examining in detail the production possibilities allows to identity the extent of technological change, production costs, byproducts, and greenhouse gas (GHG) emissions. Finally, a U.S. agricultural model, FASOMGHG was used to predict market penetration of biodiesel, given technological progress, variety of technologies and feedstocks, market interactions, energy prices, and carbon dioxide equivalent prices.

FASOMGHG has several interesting results. First, diesel fuel prices have an expansionary impact on the biodiesel industry. The higher the diesel fuel prices, the more biodiesel is produced. However, given the most favorable circumstances, the maximum biodiesel market penetration is 9% in 2030 with a wholesale diesel price of $4 per gallon. Second, the two dominant sources of biodiesel are from corn and soybeans. Sources like tallow and yellow grease are more limited, because they are byproducts of other industries. Third, GHG prices have an expansionary impact on the biodiesel prices, because biodiesel is quite GHG efficient. Finally, U.S. government subsidies on biofuels have an expansionary impact on biodiesel production, and increase market penetration at least an additional 3%.

Contents

1. Introduction

Gasoline and diesel fossil fuels are significant sources of greenhouse gas (GHG) emissions particularly carbon dioxide, amounting to approximately 31% of U.S. emissions [52]. Such

Abbreviations: FASOMGHG, Forest and Agricultural Sector Optimization Model Greenhouse Gas; EPA, Environmental Protection Agency; GHG, greenhouse gas; GWP, Global Warming Potential; IPCC, International Panel on Climate Change.

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1364-0321/$ – see front matter
doi:10.1016/j.rser.2010.05.008

emissions contribute to the greenhouse effect, causing the earth to become warmer and precipitating climate change as extensively discussed in Intergovernmental Panel on Climate Change [1]. On the other hand if society were to widely use biodiesel in place of fossil fuels this would potentially reduce emissions since biofeedstocks absorb CO_2 from the atmosphere during growth and release it upon combustion of the feedstock or the energy products derived from them. Thus biofuels in part recycle carbon dioxide mitigating greenhouse gas emissions and in turn slow down climate change. In addition biofuels have at least five other potentially beneficial characteristics:

- Biofuels are renewable.
- Biofuels could reduce the amount of petroleum imports required in many countries in turn, improving the balance of payments, increasing national energy security, and reducing reliance on imports from potentially political unstable areas of the world.
- Biofuels produced on a large scale can reduce demand for fossil fuels and could potentially constrain the growth in fossil fuel prices.
- Biofuels often have cleaner tail pipe emissions and also contain oxygen that when blended with fossil fuels reduces emissions of hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM), mercury, and sulfur dioxide (SO_2), although they tend to increase NOX emissions [2–12,42,43].
- Biofuels use of agricultural and forestry feedstocks provides another market for commodities boosting agricultural prices and producers' incomes.

2. Analysis of biodiesel market penetration

Biodiesel production rapidly expanded from about 5 million gallons in 2001 to 250 million gallons in 2006 [13]. Even though high oil prices have lately tended to reduce biodiesel production, several forces may contribute to long-term expansion in the biodiesel industry.

- High petroleum prices are raising diesel prices and the likely increasing costs of future oil production. Depletable resources follow Hotelling's [44] prices in the long run and tend to increase over time, as petroleum is depleted.
- Government mandates, such as the provisions of the Energy Independence and Security Act of 2007 [54] that includes mandates of up to 36 million gallons of biofuels.
- The public and government's concern over global warming may provide a value for biodiesels CO_2 recycling characteristics. The U.S. government has discussed the use of GHG emission price in a cap and trade system, such as in the Lieberman-Warner Climate Security Act of 2008 [14].

There are also negative forces that hinder the expansion of the biodiesel industry:

- Cost of feedstocks have risen rapidly threatening industry viability.
- U.S. biofuel subsidies are set to expire at the end of 2009.
- Large energy requirements for ethanol may push soybean oil prices above breakeven points.

The purpose of this research is to predict biodiesel market penetration given a wide variety of issues. The issues examined in this research are:

- The imperfect nature of biodiesel substitution for conventional diesel. Several technical problems will arise from large-scale production of biodiesel and is discussed extensively in the next section.
- An agricultural simulation model, FASOMGHG, is updated to include a biodiesel industry. The simulation model can help predict biodiesel market penetration and capture market interactions. The biodiesel industry competes with other industries for feedstocks and supplies a variety of byproducts.
- The agricultural model allows simulation as if the United States had a cap and trade system on greenhouse gas emissions. Thus, an equivalent carbon price can predict market penetration of biodiesel.
- The simulation model can help predict biodiesel market penetration given a variety of fossil fuel prices. For instance, higher fossil fuel prices raise an agricultural producer's cultivation, harvesting, and processing costs, but also boost prices for biodiesel.
- The agricultural model can simulate the biodiesel market penetration, if the United States government continues or removes the subsidies on biofuels.

Clearly the long-term effects of these forces cannot be fully observed in today's world as we have never simultaneous high petroleum prices, high domestic U.S. GHG emission prices, elapsed subsidies, and high competition from ethanol. Consequently, we employ an agricultural model that incorporates:

- Lifecycle and more generalized procedures that calculate the GHG offsets of biofuels.
- Competition from ethanol production.
- Competition from electricity production from biomass and manure.
- Renewable fuel standard requirements.

In doing this we follow a number of previous studies and use an agricultural sector simulation model. Namely, we follow studies on:

- Lifecycle accounting as in Wang et al. [56] or Mann and Spath [15] doing our own analysis of GHG consequences.
- Ways agriculture might modify production patterns in the face of GHG mitigation alternatives as in Adams et al. [16], Callaway and McCarl [17], McCarl and Schneider [18], Antle et al. [19], Lewandrowski et al. [20], Lee et al. [45], and US EPA [53].
- Ways agriculture might alter production patterns in the face of higher energy prices as analyzed in Francl [21], McCarl et al. [46], USDA Office of the Chief Economist [51], Antle et al. [22], Konyar and Howitt [23], and Schneider and McCarl [24,27].
- Ways agriculture might react to biofuel activities: Tyner et al. [25], McCarl et al. [26], Schneider and McCarl [27], Lee, McCarl, and Gillig [45], and US EPA [53].

3. Biodiesel fuel properties

Biodiesel is not a perfect substitute for diesel fuel and hence this section examines the compatibility between these fuels using #2 diesel as the basis. This discussion of fuel properties is based on using methanol as an input, because methanol is the cheapest alcohol and the most widely researched. The fuel properties change if other alcohols are used [28,5,10,12].

The most important property of diesel fuel is the cetane number. Diesel engines do not have spark plugs. The engine's piston compresses the fuel and air mixture until heat and pressure ignite the mixture. This ignition point is identified by the cetane number. Cetane numbers for several fuels are listed in Table 1. Conventional diesel fuel generally has cetane numbers ranging

Table 1
Biodiesel and diesel fuel properties.

Characteristics	Units	Diesel fuel #2	Soybean oil biodiesel	Tallow biodiesel
Cetane number	100%	40 to 52	45 to 56.9	58.8 to 70
Flash point	°C	60 to 72	131	117
Cloud point	°C	−15 to 5	−3 to 3	12 to 16
Pour point	°C	−35 to 15	−7 to 19	6 to 13
Higher heating value	BTU/Gal.	138,700	130,995	129,022
Lower heating value	BTU/Gal.	128,700	120,201	–

Sources: Barnwal and Sharm [57], Davis and Diegel [40], Graboski and McCormick [43], Shay [9].

between 40 and 50, with higher quality diesel fuels having higher cetane numbers [5,29, pp.104–106]. Biodiesel made from unsaturated oils like soybean oil has comparable cetane numbers to conventional diesel while biodiesel made from saturated oils like tallow have higher cetane numbers [3,5].

Biodiesel has three benefits when compared to #2 diesel. First, biodiesel can be blended with diesel fuel up to 100%. Second, biodiesel has a higher flash point. The flash point is the minimum temperature the fuel must be heated to ignite the vapor and air mixture. The U.S. Department of Transportation defines a nonhazardous fuel as one with a flash point higher than 90 °C [3,5,11,43]. As shown in Table 1, #2 diesel is considered hazardous while soydiesel and tallow diesel are not. Finally, pure biodiesel has better lubrication properties than #2 diesel. Biodiesel helps to lubricate the fuel pump and fuel injectors, which could extend engine life [3,5,43].

Biodiesel has unfavorable cold fuel properties as measured by the cloud and pour points. Cloud point is the temperature that causes the fuel to form wax on the fuel filter, thus clogging it, whereas pour point is the temperature the fuel turns into a gel, impeding fuel flow. The cloud point and pour point for soy-biodiesel (Table 1) are approximately 0 °C and −5 °C, while tallow biodiesel has much higher cloud and pour points. Number 2 diesel can have a cloud point as low −15 °C and a pour point as low as −35 °C. Thus, biodiesel may not be usable during winter where temperatures dip below freezing, preventing large-scale market penetration [3,43].

Biodiesel contains lower energy than diesel. The lower energy content of biodiesel reduces torque, acceleration, and miles per gallon rating of the vehicle [5,43,30]. Researchers use two measures of energy content. The higher heating value (HHV) is the combustion energy plus the energy to vaporize water, while the lower heating value (LHV) only includes the combustion energy [5,31]. Researchers use LHV, because vaporized water does not contribute to an engine's power. Thus, biodiesel contains approximately 93.40% the energy as diesel fuel when measure in gallons and using the LHV.

Biodiesel has more potential problems such as oxidation [2,3,43,11], microbial growth from dissolved water [5,43,9], deposit accumulation in tanks [3,43], and degradation of engine gaskets and seals [30,43,9].

4. Agricultural sector modeling – FASOMGHG

This research used the Forest and Agricultural Sector Optimization Model Greenhouse Gas (FASOMGHG) to capture market interaction [32]. FASOMGHG is a large mathematical programming, price endogenous model, and for a 25-year agricultural only implementation consists of approximately 60,000 equations and 460,000 variables. FASOMGHG is written in the General Algebraic Modeling System (GAMS) and the solver, CPLEX, finds the optimal market prices that maximize the welfare from consumer' plus producers' surpluses for each market. With a large number of markets, FASOMGHG accounts for the opportunity costs and byproducts of biofuel production [26].

The U.S. is divided into 63 agricultural production regions in FASOMGHG. Each region has unique climate and different economic opportunities. The producers in each region process the agricultural commodities into 56 primary crop and livestock products, which are listed in Table 2. Furthermore, the producers can process the primary commodities into 39 secondary products and shown in Table 3. The primary and secondary activities are aggregated into 11 regions and shown in Table 4 [32,26]. Biodiesel production could occur in any of the 11 regions.

FASOMGHG includes an international sector and decomposes the world into 27 trade regions and U.S. trade depends on the commodity and region of the world. Biodiesel is currently not traded and no international markets are included for this biofuel. However, corn, soybeans, soybean meal, and soybean oil have international trade possibilities along with a number of other commodities [32].

5. Producing biodiesel

This section describes the sources for biodiesel feedstocks and the representation of their existing markets in the agricultural sector model. Further, a brief overview about biodiesel production, greenhouse gases and technology are discussed and how they are incorporated into FASOMGHG.

Table 2
Primary crops and livestock.

Category	Activity
Primary crops	Barley, citrus, corn, cotton, hay, oats, potatoes, rice, silage, sorghum, soybeans, sugar beets, sugarcane, tomatoes, and wheat
Energy crops	Hydrid poplar, switchgrass, and willow
Livestock	Beef cattle, dairy cattle, hogs, horses and mules, poultry, and sheep
Misc.	Eggs

Source: Adams et al. [32].

Table 3
Major secondary products.

Category	Activity
Animal products	Beef, chicken, edible tallow, non-edible tallow, pork, turkey, and wool
Bio-energy	Biodiesel, ethanol, and electricity
Corn wet mill	Corn oil, corn starch, corn syrup, dextrose, high fructose corn syrup, and gluten feed
Dairy products	American cheese, butter, cream, cottage cheese, ice cream, and milk
Potato products	Dried potatoes, frozen potatoes, and potato chips
Processed citrus products	Grapefruit and orange juice
Refined sugar items	Refined cane sugar and refined sugar
Soybeans	Soybean meal and soybean oil
Sweetened products	Baking, beverages, confection, and canning

Source: Adams et al. [32].

Table 4
FASOMGHG regions.

FASOM region	States
Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and West Virginia
Lake States	Michigan, Minnesota, and Wisconsin
Corn Belt	Illinois, Indiana, Iowa, Missouri, and Ohio
Great Plains	Kansas, Nebraska, North Dakota, and South Dakota
Southeast	Florida, Georgia, North Carolina, South Carolina, and Virginia
South Central	Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Eastern Oklahoma, Tennessee, and Eastern Texas
Rocky Mountains	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming
Pacific Northwest-East side	Oregon, and Washington, East of the Cascade Mountains
Pacific Northwest-West side	Oregon, and Washington, West of the Cascade Mountains
Pacific Southwest	California
Southwest	Western and central Oklahoma and all regions in Texas except eastern

Sources: Adams et al. [32]; McCarl et al. [26].

Table 5
Corn wet mill possibilities.

Input	Output
1 bushel corn	31.5 lbs of starch or 2.5 gallons of ethanol 1.5 lbs of corn oil 2.6 lbs of corn gluten meal 13.5 lbs of corn gluten feed

Sources: National Corn Growers Association [58]; Rausch and Belyea [48].

5.1. Sources of oil and tallow

Biodiesel can be made from soybean oil. Agricultural producers harvest soybeans and could sell them to the cattle feed markets, export them, or sell them to a soybean crushing facility. If soybeans are crushed, then 1 pound of soybeans yields about 0.40 pounds of soybean meal and 0.19 pounds of oil. Soybean meal is exported or used in animal feeds while the soybean oil is sold in existing markets or converted to biodiesel.

Biodiesel can also be made from corn oil. Producers harvest corn and sell it to the domestic feed markets, domestic ethanol production (using the dry grind process), exports, or corn wet milling. The corn wet mill creates a variety of products which are shown in Table 5 and is the source of corn oil. Thus, biodiesel producers can convert this oil into biodiesel.

Tallow is a byproduct of the beef cattle industry and is in the form of edible and non-edible tallow. Each hundred pounds of meat yields about 5.38 pounds of edible tallow and 10.97 pounds of non-edible tallow [50]. Tallow is sold either to the domestic animal feed markets or to the biodiesel industry.

Yellow grease is waste cooking oil from restaurants that contains less than 15% free fatty acids. The estimated amount of yellow grease is proportional to the domestic consumption of soybean and corn oils (the two largest oil sources in the U.S.). Each pound of oil consumed in turn creates about 0.127 pounds of yellow grease. The proportion is derived from a 5-year average of the data in Canakci [2].[1] Yellow grease is sold either to the domestic animal feed markets or to the biodiesel industry.

[1] This ratio may increase as society incorporates more infrastructure that collects and processes yellow grease. Unfortunately, at this time, we do not have good estimates how this ratio will change.

5.2. Biodiesel production

The most common biodiesel production process has two inputs: vegetable oil and wood alcohol. The process creates two outputs: biodiesel and glycerol. The inputs required and outputs created depend upon chemistry and for the soybean oil case are shown in equation 1. This methodology is used to calculate the yields for the other biodiesel feedstocks.

$$1\ \underset{264.08\,\text{kg}}{\text{oil(triglyceride)}} + 3\ \underset{96\,\text{kg}}{\text{methanol}} \rightarrow 3\ \underset{275.48\,\text{kg}}{\text{biodiesel}} + 1\ \underset{92\,\text{kg}}{\text{glycerol}} \quad (1)$$

The theoretical biodiesel yields are shown in Table 6. The chemical yield coefficients are approximate, because chemical densities change with temperature.

Observed biodiesel yields are lower than the above theoretical yields, due to conversion and recovery efficiencies. Conversion efficiency is the percentage of oil chemically converted to biodiesel. Research indicates this efficiency ranges from 90 to 99% [28,43,11,12]. The recovery efficiency is the percentage of biodiesel that can be separated from the chemical mixture and is assumed to be 99%, because the biodiesel and glycerol separate into layers [28,5,12]. Consequently, the researchers set the conversion efficiency to 98%, which yields a practical efficiency of 97%. The practical yield is multiplied with the chemical yields in Table 6 to obtain the likely yields.

The production possibilities for glycerol were not included in our modeling framework, because a large biodiesel industry could easily saturate the glycerol supply, causing the market price to decrease [33,34]. For instance, the current U.S. glycerol production is around 700 million pounds [55] and 18 biodiesel biorefineries with production capacities of 50 million gallons could supply this market.

5.3. Carbon emission offsets

Greenhouse gas (GHG) emissions, offsets and sequestration are included in the modeling framework for carbon dioxide, methane, and nitrous oxide. The emissions accounting spans the life-cycle of the commodities spanning from input manufacture, crop plowing, planting, and harvesting, transporting feedstocks to the biorefinery, converting them into biodiesel, transporting the biodiesel to the retail market, and consuming the biodiesel in the transportation sector.

The life-cycle emissions for soy-biodiesel are shown in Table 7 and were derived from Sheehan et al. [10]. The life-cycle emissions show the amount of greenhouse gas offsets in metric tons for 1000 gallons of soy-biodiesel that substitutes for diesel fuel. The offset emissions include the lower energy content of biodiesel. Furthermore, the greenhouse gas efficiencies are also shown. For example,

Table 6
Theoretical biodiesel chemical yields.

Source	Oil density (kg/l)	Biodiesel density (kg/l)	Biodiesel chemical yield (gal/gal of oil)	Biodiesel chemical yield (gal/lb of oil)
Corn oil	0.9095	0.8840	1.0437	0.1378
Soybean oil	0.9138	0.8850	1.0474	0.1376
Tallow	0.8980	0.8756	1.0348	0.1384
Yellow grease	0.9117	0.8840	1.0461	0.1378

Sources: Barnwal and Sharma [57]; Domalski et al. [41]; Food and Agricultural Organization [59]; Fukuda et al. [42]; Graboski and McCormick [43]; Srivastava and Prasad [11].
Note: More biodiesel per gallon is created from oil because the gains in the chemical reaction and processing gains, where biodiesel has a lower density and occupies more volume.
Note: The density and composition for yellow grease oil is the average of corn and soybean oils.

Table 7
Greenhouse gas emissions for 1000 gallons of soy-biodiesel.

GHG	Amount (metric tons)	GHG efficiency (%)
Carbon dioxide	−22.8629	78.5
Methane	−0.00021	2.57
Nitrous oxide	−0.00024	66.1
Total	–	77.9

Source: Derived from Sheehan et al. [10].

each gallon of soy-biodiesel created recycles 78.5% of the carbon dioxide while the remaining carbon dioxide comes from fossil fuels. The total greenhouse gas efficiency uses the IPCC 100-year Global Warming Potential of gases to bring them into common units. Biodiesel produced from other feedstocks also have similar greenhouse gas efficiencies, since most the GHG offsets come from the tailpipe emissions of the vehicles. However, FASOMGHG allows complex interactions of greenhouse gases. For example, biodiesel producers crush more soybeans for biodiesel and hence produce more soybean meal. This soybean meal is sold to cattle producers, potentially increasing methane gases from the enteric fermentation of the cattle's digestive systems.

5.4. Technology

Looking to the future for biodiesel is how technology will impact the industry. Technological improvement will not likely come from the conversion and recovery efficiencies for biodiesel production, because they are quite efficient at 97% of theoretical. Thus, these efficiencies do not change in the agricultural model. Technological improvement will likely come from improvements in crop yields. As producers grow more crops, then more crops are provided to the markets. The USDA projected crop yield improvements were incorporated into the agricultural model [35].

Technological improvement can also be incorporated by having production costs decrease over time or genetic engineering improves oil content in crops. These alternatives were not examined because this paper is already quite lengthy.

6. Economic cost of biodiesel production

The FASOMGHG agricultural sector model includes two types of costs: Endogenous and exogenous. The oil feedstock costs are endogenous and determined within the agricultural model, while the biodiesel prices, feedstock processing, capital, storage, and transportation costs are exogenous and fixed. Thus, the modeling assumption is biodiesel refineries are small producers, supplying biodiesel competitively to the transportation fuels market.

The biodiesel production costs include costs for labor, overhead, methanol, catalyst, electricity, natural gas, steam, water, waste disposal, local taxes, insurance, and maintenance. The operating costs depend on which oil source is converted to biodiesel and is shown in Table 8. The costs are in 2000$ and the virgin oils are corn, soybean, and tallow. The operating costs are higher when using yellow grease, because yellow grease uses an acid catalyst while the processes for the other oils use an alkaline. Yellow grease contains high levels of free fatty acids. An acid catalyst ensures a high conversion rate and does not require pretreatment to remove the free fatty acids [2,5,12].

Table 8
Biodiesel costs in 2000$.

Type	Virgin oils	Yellow grease
Feedstock costs	Endogenous	Endogenous
Operating costs	$0.76	$1.591
Capital costs	0.0628	0.0628
Transportation and storage costs	0.05	0.05

Sources: Graboski and McCormick [43]; Haas et al. [36]; Reynolds [49]; Zhang et al. [60].

Haas et al. [36] estimated a 10 million gallon facility would have a real capital cost of $9.62 million in 2000$. For a capital life of 10 years, and a discount rate of 8%, under continuous compounding, the annual capital cost is $0.0628 per gallon. Moreover, the capital costs do not include glycerol refining.

The last cost is storing and transporting the biodiesel to the retail market. Biodiesel is relatively a new industry and is assumed to be transported to markets in a fashion similar to ethanol. The assumption is the biorefineries are relatively small with 10 million gallon capacity, and are constructed near their feedstocks, but are also constructed within 300 miles of the biofuel's retail market. The biodiesel refinery transports biodiesel by truck to petroleum product terminals and biodiesel is stored in its own tank. When biodiesel is ready to be transported to the retail market, it is blended with diesel and transported by truck. This analysis uses a real cost of 5 cents per gallon to transport and store the biodiesel after it leaves the biorefinery [49].

7. Biodiesel market penetration

FASOMGHG is used to predict the market penetration for biodiesel. There are two important assumptions about market penetration. First, the diesel fuel markets remain the same size. Thus, any increases in biodiesel production reflect increased market penetration. Second, no problems are encountered when the biofuels are blended with petroleum-based fuels, such as using biodiesel during winter months. FASOMGHG is used to solve for three scenarios: Varying fossil fuel prices, carbon equivalent price for greenhouse gases, and the removal of U.S. federal government subsidies.

The predicted market penetration includes the U.S. government subsidy of $1.00 per gallon for corn, soybean, and tallow biodiesel, and $0.50 per gallon for yellow grease biodiesel [37]. The production period ranges from 2000 to 2030 with 5-year increments. The wholesale diesel fuel prices are exogenous and are varied over the range $1 to $4 per gallon, agreeing with the 25-year energy price forecasts from the National Energy Modeling System [47].

7.1. Fossil fuel prices

The predicted U.S. biodiesel market penetration is shown in Fig. 1 and Table 9. The biodiesel price is adjusted for the lower

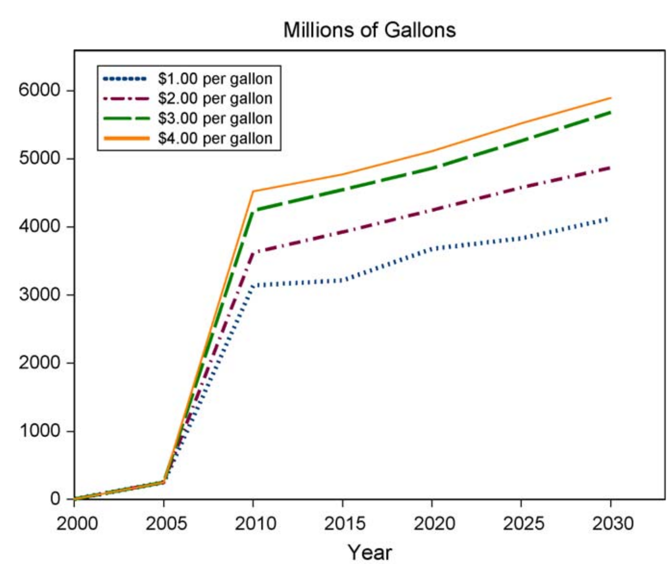


Fig. 1. Aggregate U.S. biodiesel production.

Table 9
Results from FASOMGHG.

	2000	2005	2010	2015	2020	2025	2030
Biodiesel (millions of gallons)							
Diesel Price \$1, Carbon Price \$0	5.00	250.00	3141.95	3214.80	3676.90	3832.03	4126.01
Diesel Price \$2, Carbon Price \$0	5.00	250.00	3621.59	3924.69	4246.17	4579.34	4866.99
Diesel Price \$3, Carbon Price \$0	5.00	250.00	4241.18	4546.23	4859.64	5263.62	5680.96
Diesel Price \$4, Carbon Price \$0	5.00	250.00	4521.27	4773.26	5111.88	5520.92	5893.27
Sources of biodiesel (millions of gallons and diesel price is \$2)							
Soybean Biodiesel	3.65	204.48	1494.90	1498.60	1626.27	1644.19	1566.49
Corn Biodiesel	0.35	19.05	1857.08	2151.20	2345.24	2657.77	3019.72
Yellow Grease	0.62	15.41	160.48	162.65	161.55	161.93	162.15
Tallow	0.37	10.90	109.10	112.14	113.23	115.59	118.60
Biodiesel (millions of gallons)							
Diesel Price \$2, Carbon Price \$0	5.00	250.00	3621.59	3924.69	4246.17	4579.34	4866.99
Diesel Price \$2, Carbon Price \$10	5.00	250.00	3701.77	4014.27	4375.04	4750.70	5169.81
Diesel Price \$2, Carbon Price \$25	5.00	250.00	3887.12	4233.21	4539.30	4877.54	5260.09
Diesel Price \$2, Carbon Price \$50	5.00	250.00	4275.50	4400.60	4841.18	5147.10	5601.48
Diesel Price \$2, Carbon Price \$100	5.00	250.00	4324.06	4640.45	4994.63	5250.35	5517.39
Biodiesel (millions of gallons) (gov. subsidies are removed)							
Diesel Price \$1, Carbon Price \$0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diesel Price \$2, Carbon Price \$0	5.00	180.00	184.97	185.53	185.19	185.25	185.32
Diesel Price \$3, Carbon Price \$0	5.00	250.00	2312.08	2386.09	2557.70	2862.56	3210.30
Diesel Price \$4, Carbon Price \$0	5.00	250.00	3043.82	3086.35	3330.86	3633.27	4003.98

energy content. Further, U.S. biodiesel production is constrained to its known production levels, which were 5 million gallons in 2000 and 250 million gallons in 2005. FASOMGHG clearly shows that higher diesel fuel prices translate into higher biodiesel production. However, the estimated biodiesel production is 5.9 billion gallons in 2030, when the wholesale diesel fuel price is \$4 per gallon. The annual U.S. diesel production is approximately 64.3 billion gallons in 2007 [38], attaining a maximum market penetration of 9% in 2030.

The sources for biodiesel are shown in Fig. 2 and Table 9 when the diesel fuel price is \$2 per gallon. The primary feedstock for biodiesel is corn oil and the next largest source is soybean oil. The rapid use of corn oil results from the growth of the wet corn mill industry because this industry is also a significant source of ethanol. Finally, producers utilize little tallow, lard, and yellow grease, because these sources are limited and byproducts of other industries. For example, tallow is a byproduct of the cattle industry and the primary drive for raising cattle is the consumers' demand for beef. Likewise, yellow grease is a byproduct of the restaurant industry and this industry is limited by consumer demand for eating out.

7.2. Greenhouse gas prices

FASOMGHG was used to predict the market penetration of biodiesel given if a market price existed for GHG emissions. The GHG price uses the IPCC 100-year Global Warming Potential (GWP) as an exchange rate among GHGs [39, pp. 726–771]. The GWP defines carbon dioxide equals 1, methane as 21, and nitrous oxide as 310 [7,32, p. 114]. The carbon equivalent price is exogenous and ranges from \$0 to \$100 per metric ton, because Schneider and McCarl [24] have shown this price range is effective in reducing greenhouse gas emissions.

The model predicts the U.S. aggregate biodiesel production for various carbon dioxide equivalent prices in Fig. 3 and Table 9, and the wholesale diesel fuel price is set at \$2 per gallon. Higher carbon equivalent prices have a small expansionary impact on the

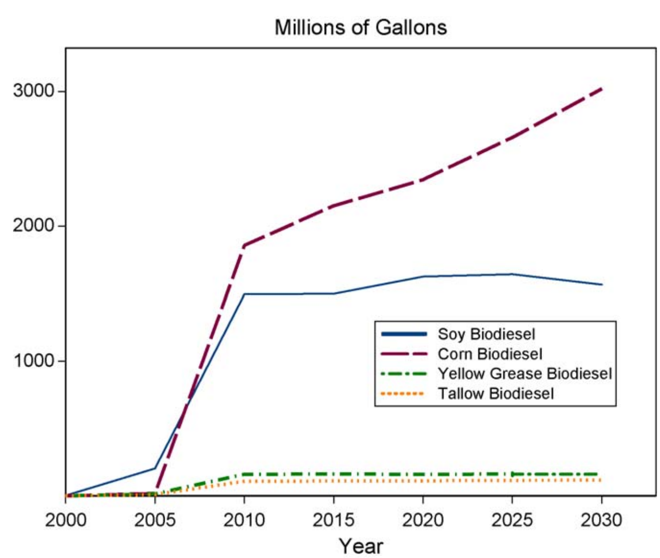


Fig. 2. Sources of biodiesel.

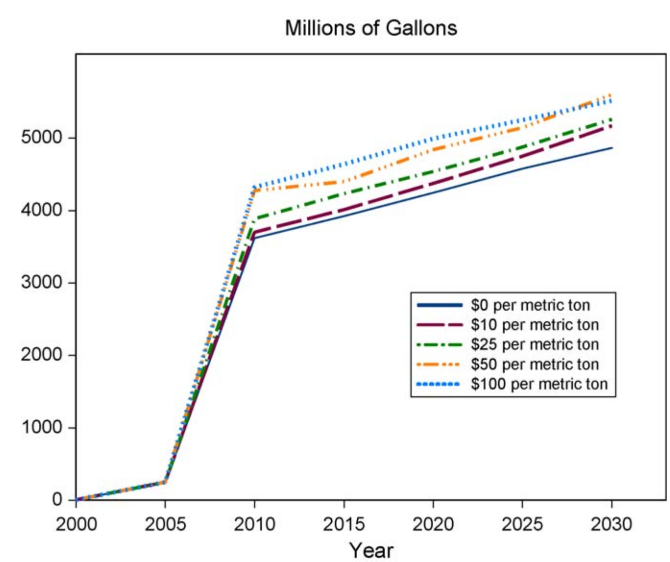


Fig. 3. Aggregate biodiesel production for various carbon dioxide equivalent prices.

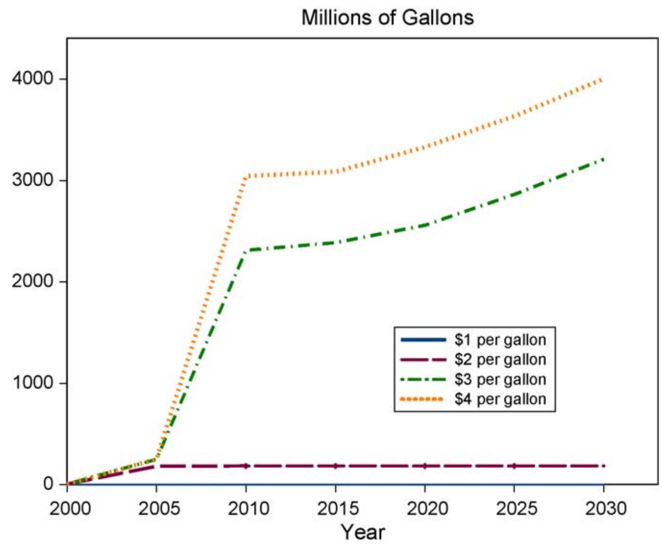


Fig. 4. Aggregate biodiesel production with no federal government subsidies.

biodiesel industry, because of the competition for the carbon credits. The carbon equivalent price rapidly expands the electric generation from co-firing agricultural and wood residues with coal. Moreover, the ethanol industry would also compete for these credits, but not as fierce at the electric generation industry.

7.3. Federal subsidies

The subsidies for biofuels are set to expire in December 2009. FASOMGHG was used to predict the U.S. market penetration for biodiesel, if the government did remove the subsidies. The results are shown in Fig. 4 and Table 9. Consequently, the federal government subsidies expand the biodiesel industry. If wholesale diesel price is a $1 per gallon, the industry does not produce any biodiesel. If diesel price is $4 per gallon, then FASOMGHG predicts the industry will produce 4 billion equivalent gallons in 2030, resulting in a market penetration of 6%.

8. Conclusions

Many scientists, politicians, and the public believe biodiesel is the cure for a dependence on petroleum fuels. However, this research paper identifies several problems with biodiesel and its potential market penetration:

- The cold fuel properties of biodiesel have to improve for large-scale penetration of biodiesel. Otherwise, biodiesel could not be used in the northern United States during winter.
- The predictions from FASOMGHG are optimistic, because diesel fuel prices do not vary within the agricultural model. Thus, producers would have no uncertainty about the future price of fossil fuels. Unfortunately, even with government subsidies, the maximum market penetration of biodiesel is no larger than 10%.
- If the U.S. government approved a cap and trade program for GHG emissions, a GHG gas price may have a small expansionary impact on U.S. biodiesel production. The electric industry would be tough competitor for the carbon credits. Extremely high carbon dioxide equivalent prices expand electricity production from co-firing agricultural residues, willow, and switchgrass. Co-firing has less processing costs and is slightly more GHG efficient.
- U.S. government subsidies has an expansionary impact on biodiesel production, but only help expand the market penetration by an additional 3% in 2030.

This research is not a death sentence on biodiesel. The biodiesel industry will have to:

- Develop a fuel additive that lowers the pour and cloud points of biodiesel, so biodiesel is usable during cold winters.
- Use genetic engineering to increase oil content or crop yields in the feedstocks.
- Find and grow new feedstocks that improve the oil yields from the feedstocks.

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